Dr. J. H. Laub

Development of a Flowmeter

History and Motivation

In 1946 Charles Engelhard Inc., a medium size instrument company in Newark, New Jersey specializing in thermal and gas-analytical instruments, was informed by its sales representative that the US Air Force Development Center at Wright Field, Dayton, Ohio was interested in the development of an obstructionless fuel gage for applications in military aircraft and for stationary installations in test cells for aircraft engines.

The desire for an obstructionless flowmeter was prompted by serious difficulties which the Air Force had experienced with two types of fuel flowmeters heretofore available. In military aircraft a mechanical fuel gage was used in which a vane was deflected by the momentum of the flow against the restoring force of a spring. The vane moved in a spiral shaped cavity with very small clearance from the wall. In several instances the meter had become clogged by impurities in the fuel, particles of metal or dirt, etc. which lodged in the clearance space and arrested the vane. The ensuing choking or even complete stoppage of the fuel flow resulted in starving and stalling of the aircraft engines and in several cases the outcome had been fatal to the pilots.

Of equal seriousness and importance had been accidents which occurred in stationary engine test installations with another type of widely used flowmeter -- the Rotameter. This instrument is a variable area type of orifice flowmeter in which a float moves inside a conical tube and indicates by its position the volume rate of flow.(Exhibit I). As the float moves along the axis of the conical tube, the area between the float and the inner wall of the tube varies; hence the name "variable area meter". This automatically adjusts the pressure drop across the float-orifice with changing flow rate and balances it against the weight of the suspended float.

The conical tubes of the Rotameters were made of glass on which scales were etched. This facilitated the reading of the float position; however, in several instances the glass tubes, though of heavy wall thickness, were ruptured and the fuel spilled into the test stand. In fact, in one particularly serious accident an explosion occurred in the test installation of a large aircraft engine manufacturer causing the loss of several lives and $11 million worth of property damage.

The problem thus was a very important and intriguing one. It was obvious to me at the same time that a flowmeter with a smooth bore and without fluid exposed measuring elements, if successful, should have many applications in other fields. It should have important advantages in the chemical industry where acids and alkalis can cause severe corrosion and maintenance problems in flowmeters with fluid exposed measuring elements, or in mining and metallurgical operations where slurries can cause severe damage by abrasion. In food processing plants flowmeters for the measurement of beverages, milk, fruit juices, etc. must meet very rigid sanitary requirements. An instrument with a perfectly smooth bore should be very attractive because of its ease of cleaning.

Furthermore, an obstructionless flowmeter causes the smallest possible pressure loss, i.e., the same as an equivalent length of the pipe line. This is a distinct advantage where the available line pressure is too small to overcome the pressure drop of a flowmeter with obstructing elements. Where large flowrates are involved the small pressure loss of an obstructionless flowmeter may result in substantial savings in pumping costs.

It was also apparent at this stage that a flowmeter which produced an electrical output signal directly would be very desirable. In many applications an electrical

read-out, recording, telemetering or control is required and instruments operating on a mechanical principle need an additional device for conversion into an electrical signal.

The Air Force specifications also called for minimum weight and space and for a rugged design to withstand severe shock and vibration typical of the military aircraft environment. High accuracy had to be maintained over a wide range of ambient and fluid temperatures.

At the time, I was General Manager of Charles Engelhard, Inc., and Hanovia, two of the companies of the Engelhard Group in Newark, New Jersey (see enclosed resume). I was directly responsible to Mr. Charles Engelhard, the President and owner. The products of Charles Engelhard, Inc. at the time were precious metal thermocouples and resistance thermometers, recorders of the chopper bar type and gas analyzers based on the thermal conductivity principle. Most of the designs were modifications of models originally developed by a German company, W.C. Heraeus Company, in Hanau with which Mr. Engelhard was closely associated in other fields as well, particularly precious metals. The company, up to that time, had developed only one proprietary instrument, i.e., an air-fuel ratio gage which had not been very successful. The sales of the company had been pretty stagnant for a number of years, at a level of approximately a quarter million dollars per annum. I was anxious to expand the diversity of its line of products; however, Mr. Engelhard, who was then in his high seventies, was very reluctant to spend money for R and D. The company had not shown a profit over a period of years and he did not feel like injecting fresh capital to finance its growth. His attitude, though perhaps understandable, was not very helpful throughout this project which thus had to be pursued "on a shoestrong". The company had only three technical employees, none of them with an academic degree.

The addition of a flowmeter to the line of instruments manufactured and sold by the company seemed to be reasonable and compatible in principle. No obstructionless flowmeter existed at the time; all conventional instruments operated with elements directly exposed to the fluid. The problem of measuring the flow rate with sensors not in contact with the stream seemed very challenging to me but also difficult to accomplish.

Conception

I had given considerable thought to potential solutions to the problem but had discarded them as not being practical and worth trying. From past experience I had made it a principle to visualize the actual performance of a device as realistically as possible under the environmental and operational conditions in which it would be used.

One morning, while shaving in the bathroom (where creative ideas usually are born) I noticedhow fast heat was transmitted through the line and the faucet when the hot water was turned on. The thought occurred to me then that it might be possible to inject heat into a fluid line from the outside and to sense the temperature changes brought about by variations in the flow rate. Our company produced temperature sensors in the form of resistance thermometers and thermocouples which had been used for other applications with comparable specifications of accuracy, sensitivity and temperature range. This approach did not, therefore, appear to be too far out of the realm of competence and experience of our technical staff.

Bread Board Model

I decided to try the feasibility of the concept by building a simple bread board model. The only employee I could use on this part of the project was Mr. John Kremer, who was in charge of the design section. Although Mr. Kremer did not have an academic degree, he had considerable experience in electro-mechanical instrumentation and had been with the company for about 25 years. I gave Mr. Kremer sketches (similar to Exhibit II) of a transducer suitable for our experiments. From these, he made working drawings of the device which consisted of a copper tube, 1 inch ID and 1/16" wall, 12 inches long, with end fittings for host connections. Copper was selected because of its high thermal conductivity. The outer surface of the tube was coated with a very thin layer of enamel lacquer for insulating the measuring elements. We decided to use resistance thermometers of pure nickel wire as temperature sensors. They could be wound as tight coils on the surface of the copper tube, assuring intimate thermal contact with it through the insulation.

The resistance of pure nickel wire changes approximately 6/10 of 1% per degree centigrade. With a total resistance of 25 Ohms for each coil, I calculated that a difference of 0.006 x 25 or 0.125 Ohms could be expected for each degree centigrade temperature difference between the upstream and the downstream resistance thermometers. An unbalance of this magnitude can be easily detected and measured in a Wheatstone bridge in which the two resistance thermometers form two of the arms, as shown in Exhibit III.

We used a heater coil of Michrome wire for the injection of heat between the two temperature sensors. It also was wound in intimate contact with the tube and supplied with power from a battery through a rheostat for regulating the input to the heater. Nichrome wire was selected because its thermal coefficient of resistance is negligibly small and makes the wattage input to the heater practically independent of the temperature, over a wide range. The bridge can be balanced for a given rate of flow by adjusting a variable resistor in one arm of the bridge. A micro-ammeter in the bridge diagonal served as Null indicator (see Exhibit III).

The first tests were made by running tap water through the transducer and a regulating valve and measuring the rate of flow by a Rotameter in the line. For this experiment we bought a Rotameter with a maximum range of 50gal/minute and an accuracy of 1% of full scale. It was calibrated for both water and gasoline by the manufacturer, Fischer and Porter. When the water was first turned on, we were astonished and elated to see the pointer of the Null instrument swing so fast and come to rest in the new position after a step change in the flowrate. We had expected (and feared) a much slower response because of the thermal time lags involved in heating (or cooling) the column of fluid between the point of injection and the downstream thermometer. Our conception of the principle of operation of the instrument was, at the time, that heat is carried by convection in the bulk of the fluid from the area of injection to the area of measurement of the temperature. A later analysis of the mechanism involvedin the operation of the instrument showed that this concept was wrong. The much faster than expected response could be explained satisfactorily then by the fact that only the very thin boundary layer of the fluid takes part in the transfer of heat and that its thermal inertia is very much smaller than that of the fluid bulk.

Another indication that something was wrong with our theory was the pronounced effect of the temperature of the water on the meter. It was much greater than could be expected from the equations for the simple bulk convection theory which show that the only fluid parameter sensitive to heat, i.e., the specific heat, varies very little with temperature.

Otherwise, the experimental model behaved pretty much as expected. When the wattage input to the heater coil was held constant and the water flowrate was increased, the temperature difference between the upstream and the downstream thermometer, as indicated by the microammeter, decreased inversely with the flowrate, and vice versa.

Improvements

It was obvious that we had to do something about the extreme sensitivity to fluid temperature since in most practical installations the fluid temperature cannot be held constant and rather will vary considerably. Also, the hyperbolic, non-linear scale resulting from reading the microammeter and holding the heater wattage constant was objectionable for many applications. In particular, it precluded the possibility of totalizing the flow by integration over time, a feature which was not necessary for some commercial applications yet desirable in many others.

The problem of temperature sensitivity was very serious and vexing. We built a closed cycle system, pumping the water from a tank which could be heated and cooled and permitted us to vary the water temperature over a fairly wide range. Since the effect on the scale was approximately 0.7% per degree F. we thought we had developed (unnecessarily) a sophisticated thermometer instead of a flowmeter. I finally solved the problem by making the circuit automatically temperature compensating in the following manner. One of the normally "fixed", i.e., thermo-constant arms of the bridge was made responsive to the fluid temperature by adding in series with the fixed resistor a small coil of nickel wire which was wound on the outside of the transducer, adjacent to the upstream thermometer. It thus "followed" the fluid temperature and by a proper adjustment of the ratio of the fixed and the thermo-responsive resistance the bridge output becomes independent of the temperature and dependent only on the flowrate of the fluid. This arrangement worked very well; later tests on aviation fuel, for instance, showed that the error is less than 1% over a range of 50 degrees centigrade.

The linearization of the scale of the instrument was accomplished in the following way. Instead of operating the flowmeter in the "constant wattage mode" and measuring the temperature difference, the latter was held constant by adjusting the wattage to the heater as the flowrate varied. In this, the "variable wattage mode", the bridge, after a change in the flowrate, is returned to the balanced condition, as indicated by the Null indicator. It results in a nearly linear relationship between wattage and flowrate, over a wide range, as long as the flow is in the turbulent regime (Renolds number greater than 2,100). In many practical applications the flow is turbulent or can be made so by proper dimensioning of the transducer. An example, the scale characteristic of a flowmeter for aviation gasoline, operated in the variable wattage mode, is shown in Exhibit IV. Incidentally, the variable wattage mode of operation has the added advantage of making the bridge circuit independent of the supply voltage.

It remained to make the adjustment of the wattage automatic with varying flowrate. This was achieved by using a feed-back servoloop circuit (see Exhibit V). If the flowrate changes, the bridge becomes unbalanced; the unbalance voltage is detected, amplified and fed into a reversible induction motor which drives a rheostat in series with the heater coil. The adjustment of the wattage continues until the bridge balance is restored.

Shortly before that time, several manufacturers of instruments and control devices had come out with their first electronic type potentiometer recorders. They incorporated vacuum tube detectors and amplifiers and two-phase induction motors to drive the potentiometer. We found that one of these, made by the Brown Instrument Division of Minneapolis-Honeywell, was tailormade for our purpose and by using it we saved the trouble and the expense of developing our own servo system. The only element we could not use was the potentiometer which could not carry the load necessary for controlling the heater wattage. Mr. Kremer designed a drum type variable rheostat with brush contacts which could take the load and could be mounted in a standard instrument case which also housed the amplifier and motor, as well as a wattmeter to read rate of flow and a watthourmeter to read total flow. (See Exhibit VI.)

The variable wattage mode thus solved the problem of measuring in the turbulent regime of flow satisfactorily. In applications involving fluids in laminar flow (highly viscous, low flowrates) the constant wattage mode is usually preferable. It becomes

increasingly sensitive with decreasing flowrate; however, an instrument with a hyperbolic scale whose deflection decreases with increasing flowrate is not very desirable. We corrected these deficiencies by introducing a constant voltage opposing the bridge signal and reversing the deflection of the indicating instrument whose scale thereby becomes close to linear over a fairly wide range.

Field Trials

At this point we had invested approximately $20,000 in development without any outside funding. We realized that we had a prototype flowmeter which was suited for a trial in a stationary installation but was too heavy and bulky for airborn use. We decided to give the instrument a first trial in the field with a "friendly" customer. The Instrument Division of the du Pont Company in Wilmington, Delaware agreed to test a prototype in one of their plants on hydrofluoric acid. The instrument operated very satisfactorily over a period of several months until the previously described, home-made rheostat failed. We realized that a redesign of this component and, if possible, the entire servo control unit was desirable with the objective of eliminating the electro-mechanical mechanism of a motor-driven regulator.

In a subsequent test of another prototype it became apparent also that the time lag of the instrument was still too large for certain promising applications. The U.S. Navy at the time was interested in developing an improved ship speed indicator. The pilot tube type then in use was not entirely satisfactory because of its non-linear (square root) scale characteristic and consequent poor resolution at low speeds. Mr. Kremer designed a tear-drop shaped, streamlined transducer which scooped up the water through its tubular bore. The flowrate thus became a measure of the ship's speed through the water. The Bureau of Ships made available the towing tank of the Taylor Model Basin in Washington, D.C. for tests. This proved quite successful, except for the response time which was too slow for the purpose.

No further work was done after the two field trials since Mr. Engelhard did not want to spend any more money on research and development.

Documentation

Before releasing the prototype instruments for field tests, I had filed a patent application, on May 21, 1946, which covered the essential features of the flowmeter, in particular the automatic temperature compensation. This application matured into U.S. Patent No. 2,729,976 (see references), on January 10, 1956, after ten years in the Patent Office.

I also wrote a paper, entitled "An Electric Flow Meter" which described the instrument, as then developed, and was published in the December 1947 issue of ELECTRICAL ENGINEERING, p. 1216-1219 (Exhibit VII). It should be noted, however, that when I wrote this paper, I had not made a thorough analysis of the heat transfer mechanism which is the basis of the operation of this instrument. The equations (1) to (4) in this paper are based on the (much too) simplified assumption of heat transfer by convection through the bulk of the fluid. The results of my later analytical treatment are published in my subsequent papers, i.e., in CONTROL ENGINEERING, March 1957 (Exhibit VIII), INSTRUMENTS AND CONTROL SYSTEMS, April 1961, and ACTA IMEKO, 1964 (see references). They show that the instrument actually measures the rate of heat transfer through the boundary layer of the fluid which is proportional to the 8/10th power of the mass flowrate in the turbulent regime and to the 1/3 power in the laminar regime. These papers also treat the effect of varying fluid parameters, i.e., viscosity, thermal conductivity and specific heat as a result of changes in the composition or temperature of the fluid, the influence of the material and wall thickness of the conduit and the effect of scale formation on the inside wall. The "boundary layer theory" explains also very readily the surprisingly fast response time and the very small power requirement of the instrument. Theory and experiments show very good correlation.

Design for Production

In 1953 I left the Engelhard organization under an amicable settlement which reassigned to me my patents and patent applications for the flowmeter, subject only to shop rights for Charles Engelhard, Inc. I established myself as a consultant which provided the opportunity to devote more time and effort to the further development of the flowmeter. I then began working with Mr. Nathan Schnoll who was the founder and president

of three companies in New Jersey: Industrial Instruments Inc., a medium size company manufacturing capacitance and resistance bridges, conductivity measuring and similar devices; Industrial Devices, Inc., a small company specializing in molded plastic components; and Industrial Development Laboratories, Inc., a small development organization whose laboratory, design and limited manufacturing facilities he made available when he became interested in collaborating with me on the flowmeter.

The field trials described previously had shown that it would be desirable to eliminate the electro-mechanical servo system and necessary to improve the response time before the instrument could be released and offered for sale as a commercial product. Mr. Schnoll, with a lifetime of experience in designing instruments and components, was anxious to anticipate as many of the problems that might come up in the field as might be possible.

We decided to concentrate first on the improvement of the servoloop and developed an "all electronic" circuit with vacuum tubes for the feedback amplifier and mercury vapor thyratrons for the control of the heater power (Exhibit IX). This circuit eliminated all electro-mechanical components and was more compact than the previous one. We found, however, that the response time showed little, if any improvement. We tried to shorten it by increasing the gain of the amplifier; however, this resulted in bad "hunting" (oscillations) of the circuit and proved impractical. We were vexed by this problem for quite some time until it occurred to me that the cause might be a mismatch between the time constant of the circuit and the thermal lag of the transducer which depended on the rate of flow. I had noticed that at high flowrates a much higher amplifier gain was permissable without causing hunting than at low flowrates. In order to avoid hunting at low flowrates the gain had to be reduced much below the optimum value for operation without hunting at high flowrates. This gave me the idea of making the gain or the time constant of the circuit dependent on the flowrate instead of keeping it constant. How to do it was another question but finally the circuit emerged which accomplishes the "matching" automatically and is described in my Patent No. 2,994,222 and shown in Exhibit X. The time constant of the circuit is controlled by the delay network 38 and is the product of the capacity C of condenser 52 and the resistance R of resistor 58. It can be made to vary if instead of a fixed resistor 58, a thermistor is used which has a negative resistance-temperature characteristic. It is surrounded by a small heater 22

which is connected in series with the heater coil 12 of the transducer. If the flowrate increases, the current through the heater coils 12 and 22 will be increased automatically by the servolloop. This will result in a lowering of the resistance of the thermistor 58 and a proportional decrease in the time constant of the circuit. The reverse will happen if the flowrate decreases. By proper dimensioning of the circuit elements the time constant RC can be closely matched to the flow-variant thermal lag of the transducer. This resulted in a very substantial improvement of the response time of the instrument; it was reduced to better than 1/10 sec. for waterlike liquids which, for a thermal type instrument, is quite startling.

We then turned our attention to improving the design of the transducer with the objective of making it more rugged and easy to manufacture. Mr. Schnoll designed a number of transducers for different applications, employing materials compatible with the fluid to be measured, among them stainless steel, nickel, Hastalloy, silver, and copper. The response of these materials to unsteady heat flow, i.e., transients which follow changes in the rate of flow of the fluid, varies widely. It is very important because it can contribute significantly to the overall time lag of the instrument. An analysis shows that the response time is inversely proportional to the diffusivity of the material, i.e., the thermal conductivity divided by the product of the specific heat and density. It also depends, of course, on the thickness of the wall; it can be shown that the response time is inversely proportional to the square of the wall-thickness. One is thus enabled to compare different materials as far as their transient thermal behavior is concerned. For instance, silver has a diffusivity 25 times greater than stainless steel; hence the time lag of a silver tube with a wall of 1/8 inch is the same as that of a stainless steel tube with a wall of 1/40 inch. Fortunately, the mechanical strength of stainless steel which is an important material of construction for many applications (acids, beverages, etc.) is so much greater than that of silver that, for a given pressure a stainless steel tube of 1/40 inch wall is fully equivalent to a silver tube of 1/8 inch wall.

Another problem area encountered in the design of production models was leakage. In the earlier models a nylon spacer was used as a thermal insulator between two sections of the transducer, one of which carried the heater coil and the downstream thermometer, the other one the upstream thermomenter. With this design it was rather difficult to obtain a pressure tight seal. In several instances, the liquid had leaked through the

seal and into the space between the transcucer and the outer shield and sometimes even flooded the heater and sensor coils. Mr. Schnoll suggested the omission of the insulating spacer and the construction of the transducer from one uninterrupted length of tubing. This eliminated the spacer-leakage problem but introduced new problems inasmuch as it established a heat transfer path axially through the tube wall between the heater and the upstream sensor which partially shunted the boundary layer of the fluid. In the case of materials with poor thermal conductance such as stainless steel this was not too serious as long as the wall could be held sufficiently thin. However, this design could not be applied to metals with high thermal conductance because the axial heat flow has a disturbing effect on the performance characteristics of the instrument.

Considerable difficulties were also experienced from leakage of the end flanges until a successful technique was developed by Mr. Schnoll for joining by heliarc welding of stainless steel and other "difficult" materials.

The insulation of the measuring elements from the transducer proved to be another problem. It was necessary to keep it as thin as possible in order to reduce its thermal resistance to a minimum. Coating of the outer surface of the transducer with insulating lacquers or varnishes proved unsatisfactory because pinholes developed which shorted the coils to the tube. After many trials, a Mylar film, 1/2 mil thick and bonded to the outside wall of the tubing was adopted as a satisfactory solution.

The design of transducers for very high fluid pressures was also studied at that time. There is a practical limit to the thickness of the wall owing to its effect on the response time and linearity. A design for high pressures and yet fast response and good linearity is described in my U.S. Patent No. 2,953,022 and 3,056,295. It consists essentially of a thin walled tubular member on which the measuring elements are arranged and which is inserted or molded into a concentric tube which has adequate strength to withstand the pressure. The response time can be further improved by eddy current heating with an induction coil which eliminates the resistance of the insulation needed in case of resistance heating.

All of the improvements which the field tests had proven to be essential and the design for production were accomplished by the support of Mr. Schnoll, at a cost of approximately $50,000.

Industrial Development Laboratories, Inc. sold about 60 instruments between 1955 and 1957, with a total value of approximately $100,000. In 1957, Mr. Schnoll sold the business of Industrial Development Laboratories to Weinschel Engineering in Kensington, Maryland, because of ill health. Weinschel Engineering, a medium size company manufacturing short wave measuring instruments, sought diversification at the time but later realized that the flowmeter business was too removed from their established line, competence, and marketing capability and abandoned it after selling a few flowmeters.

Pneumo-Tachometer

As an example of an application of the flowmeter, a more recent development of a miniature version of the instrument will be described because it involved some interesting performance specifications. About four years ago, the Air Force Flight Test Center at Edwards Air Force Base in California invited proposals for a pneumo-tachometer, i.e., an instrument to measure and telemeter the oxygen breathing rate of astronauts. The frequency and depth of respiration is an important indicator of the well-being of an astronaut. Edwards Air Force Base was interested in monitoring it and telemetering it to a tracking station on the ground and specified that its size, weight, and power requirement should be so small that it could be built directly into the space helmet of the pilot. No device was acceptable which could in any way obstruct or clog the flow of oxygen or produce a loss in pressure exceeding that of the line.

Spacelabs, Inc. in Van Nuys, California, a company specializing in bio-medical instrumentation and systems, made an extensive survey of all available gas flowmeters and finally decided that the boundary layer type was the only one which had a chance of meeting these specifications. They submitted a proposal for a contract which was accepted and funded by Edwards.

I was retained by Spacelabs as a consultant on the project which resulted in the design illustrated in Exhibit XI. The instrument was supposed to measure not only the average breathing rate but to "follow" and display each respiration cycle individually. Fast response was therefore of great importance and for this reason a silver tube was selected for the transducer, with an ID of 0.207 inches and a wall thickness of 0.022 inches. The high thermal conductance of silver, however, made it necessary to

thermally insulate the upstream thermometer from the heater coil by arranging them on separate sections which were insulated with Tygon spacers.

Since the information had to be telemetered to the ground, a circuit was developed which took advantage of the inherent capability of the boundary layer flowmeter for operation in a digital rather than an analog mode. The heater can be supplied with pulsed power instead of continuous and any of the well known pulse frequency measuring methods can be used. A detailed description of this method is given in my U.S. Patent No. 2,972,885. For the pneumo-tachometer, the variable pulse width, constant frequency mode was employed, as shown in Exhibit XII in a gated 4 kc circuit which is described in Reference 4. The maximum power consumption is less than 1 watt, a negligible drain on the available supply.

The circuit was sufficiently miniaturized to fit into the space helmet, together with the transducer. Exhibit XIII shows results of measurements of the flowrate versus voltage output. They were taken on nitrogen at atmospheric pressure and show very little deviation from a linear relationship.

Spacelabs, Inc. took a license in 1962 and since then obtained several contracts from government agencies (Edwards Air Force Base, NASA Huntsville, Apollo Project) totaling over $100,000.

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6. US Patent No. 2,729,976, January 10, 1956.

7. " 2,832,018, April 1, 1958.

8. " 2,953,022, September 20, 1960.

9. " 2,972,885, February 28, 1961.

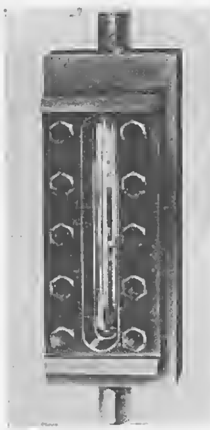
10. " 2,994,222, August 1, 1961.

11. " 3,056,295, October 2, 1962.

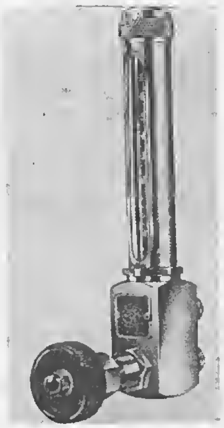
Rotameters

The rotameter falls in the general classification of a variable area flowmeter. In its simplest form, the rotameter consists of a tapered glass tube that is narrowest at the bottom. Inside the tube rests a float which is supported by differential pressure created by the annular restriction between the tube and the float. Flow is determined by reading the float position on a calibrated scale fastened to the tube. Recently, more and more manufacturers have coupled transmitters by various means to the float in order to provide remote indication.

Exhibit I: Common Flowmeter Types.

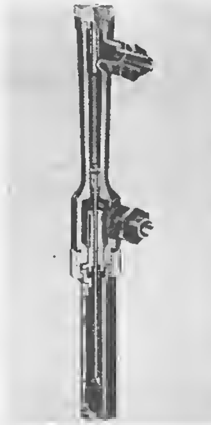


Brooks



Hoke

Manostat



Selas

Wallace & Tiernan

The Brooks Instrument Co., Inc., 1400 Series Hi-Pressure indicating rotameters utilize a standard borosilicate glass metering tube built into a flat bolted gage glass body by means of two adapter end fittings. An equalizing vent drilled into one end fitting permits the use of glass metering tubes at pressures normally beyond the safe working range of the tube without fear of metering tube rupture.

The Hoke, Inc. Flo-Gages measure flow by the variable area principle. A ball float in a precision tapered tube indicates the rate of flow by its position in the tube. Pressure on the down stream side must be atmospheric for direct reading. Four basic styles are available with a wide variety of metering units.

The Manostat Corporation offers predictability flowmeters which consist of spherical floats in tri-flat tubes. These tubes are circular in cross-section at the bottom and triangular at the top. In between, the tube has a cross-section which progressively changes from a circle to an equilateral triangle whose sides are tangent to the circle. The balls which act as floats slide in the tubes.

Schutte & Koerting Company has just added to their line of flow meters solid state electric Rotameter Transmitters. The new transmitters, which operate on an induction principle, are completely contained in a metal housing that is directly coupled to the company's "Safeguard" or metal tube rotameters. The rotameter transmitter is therefore capable of measuring and transmitting flow rates up to 200 gpm in pipelines up to 3 in. at pressures up to 600 psig.

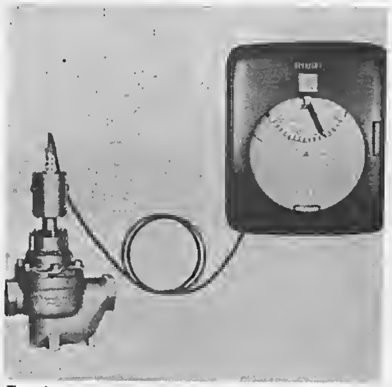
Another variation is Selas Corporation's line of Flo-Scopes for providing indication of gas flows in furnaces and atmosphere generators. These units use a flat disc as the metering float which is connected to the indicator riding in an oil-filled sight glass. The oil serves to dampen "fluttering" which might otherwise result from pressure fluctuations. When located upstream from mixing equipment, Flo-Scopes indicate separate rates of flow and permit determination of gas-air mixture ratios. Total mixture volumes may be determined by adding separate gas and air Flo-Scope readings, or by installing Flo-Scopes directly in mixture lines.

The Wallace and Tiernan Varea-Meter Transmitter is a pneumatic servo-type indicating instrument which produces a 3 to 15 psi signal proportional to flow for the operation of indicators, recorders, integrators, or controllers. It is inherently linear and easy to adjust. All major components are designed as plug-in units so fast, easy removal minimizes down time. The instrument employs magnetic detection of the float rod position. The sensor imposes no drag on the Varea-meter which might affect accuracy and sensitivity.

Turbine Flowmeters

Turbine meters are those in which the primary element located in the flow line is kept in continual rotation by the linear motion of the stream. This primary device usually is a simple propeller installed in the flow line, and either geared to a counter or actuating the counter by electrical impulses. This type meter is often used in blending systems as well as measuring fuel flow in aircraft and missiles.

Cox Turbine Flowmeters by Cox Instrument Div., The George L. Nankervis Co. are individually calibrated at numerous flow rates using either water or the standard reference fuel at 80°F. From data so obtained, the average cycles/gallon (or barrels, pounds, etc.) are calculated. This average, or "K" factor, is guaranteed to be within ±0.5% of actual flow rate. Flow rates at the 120 and 1200 cps flow points and the "K"



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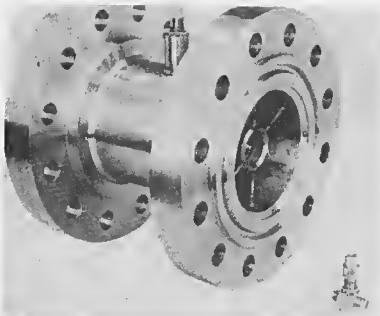
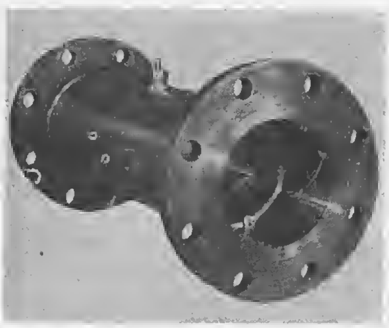


Cox



Waugh

factor are supplied for calibrating the readout. Cox turbine flowmeters are ideally suited for flow measurement and control of liquid or gaseous hydrogen, nitrogen, oxygen, and other cryogenics. Also manufactured by the Cox Div., are variable area flowmeters.

The Pottermeter by Potter Aeronautical Corp. is a volumetric flowmeter. The rotor speed is determined by the flow rate of the fluid passing through the meter. This results in an angular velocity of the rotor which is proportional to the volumetric flow rate. The total number of revolutions reliably represents the total through-put. All downstream thrust is absorbed by the flowing fluid. Special internal contours designed into the flow passage result in pressure differences across the rotor exactly counter - balancing downstream thrust.

Flanged Flow Sensors of the turbine type manufactured by Waugh Engineering Div., The Foxboro Co., are designed for long operating life under rugged operating conditions. The average design life of these units is in excess of 20,000 hours of continuous service. This is made possible in the FB-Series through the use of large over-sized stainless steel ball bearings. In the FF-Series, many years of trouble-free service is provided as there are no bearings, and the turbine spins on a film of the fluid being measured.

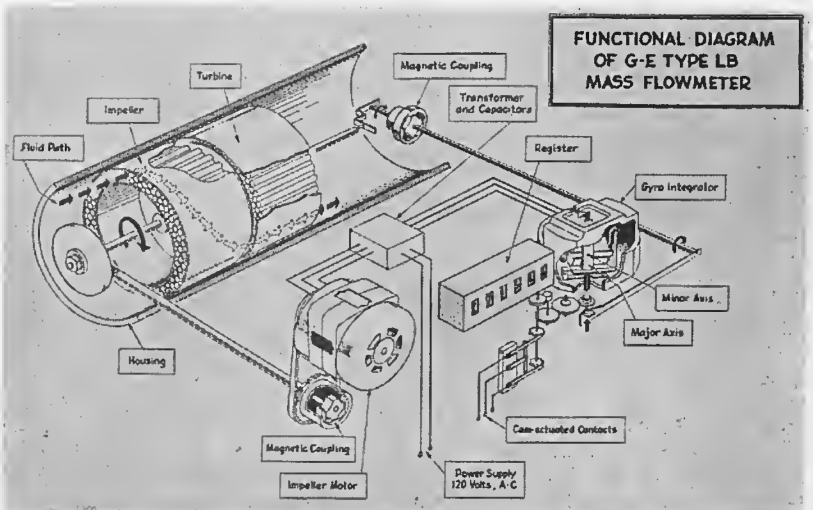
In the Sentry Equipment Corp., Vortex Type Meter the liquid enters the measuring chamber tangentially. The liquid spins in the chamber as it passes through, forming a vortex. Each gallon that passes through makes exactly the same number of revolutions of the liquid. A vane is placed in the rotating liquid to impart this rotation to a register. It is not necessary for the entering liquid to forcibly strike the vane, it simply turns the vortex.

Others

The Decker Corp. Gyroflo is a true mass flowmeter based upon gyroscopic principles. The vibrating gyro provides mass flow measurement. Features include linear calibration, high accuracy, wide dynamic range, independence of viscosity and density. It measures non-Newtonian liquids and slurries, provides bidirectional flow measurement, it is unaffected by stream turbulence and provides d-c output signal.

General Electric's gyro-integrating mass flowmeter is a simple, low-maintenance device which measures the weight of flowing fluids with high accuracy over wide ranges of flow rate, pressure, temperature and density. Compatible with automation, the flowmeter was designed to emit a series of electrical pulses, each representing a given weight of fluid. This signal can be used to operate remote counters, printers, and totalizers.

The Pioneer-Central Division of Bendix Aviation Corp. makes a line of true mass flowmeters for use in aircraft. Typical of



General Electric

Bendix

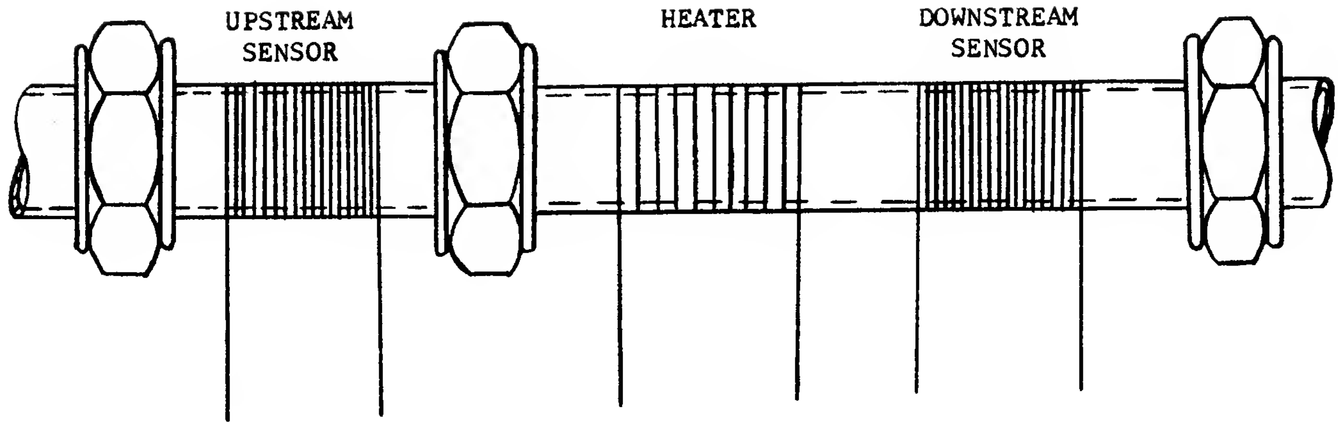


Exhibit II: Sketch of Original Flowmeter Concept.

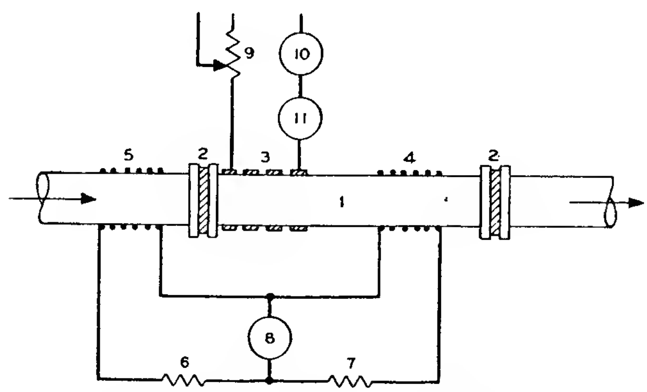


Exhibit III: Basic elements of an electrocaloric flow meter

1. *Heater tube section*
2. *Insulating spacers*
3. *Heater coil*

4, 5. *Resistance thermometers*
6, 7. *Fixed resistors*

8. *Null detector*
9. *Current regulator*
10. *Wattmeter*
11. *Watt-hour meter*

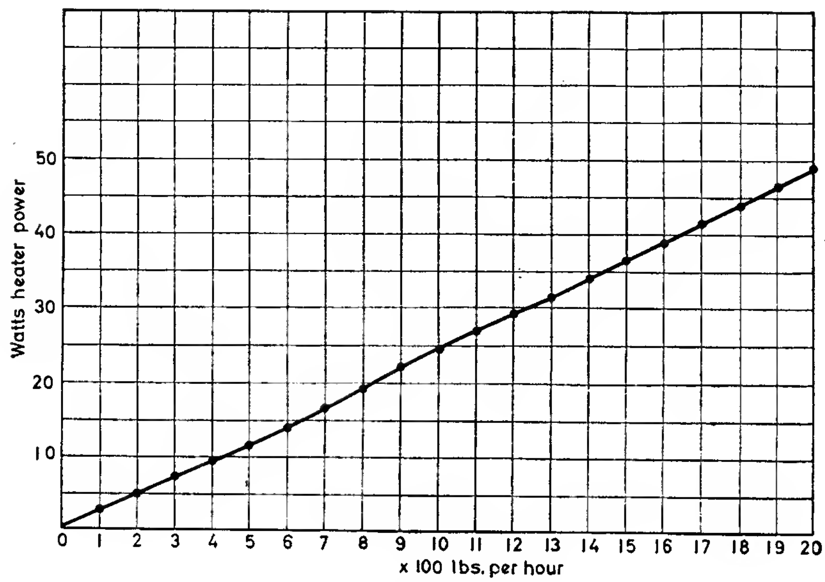


Exhibit IV: Typical Calibration Curve Aviation Gasoline Flow Meter 1-inch Diameter

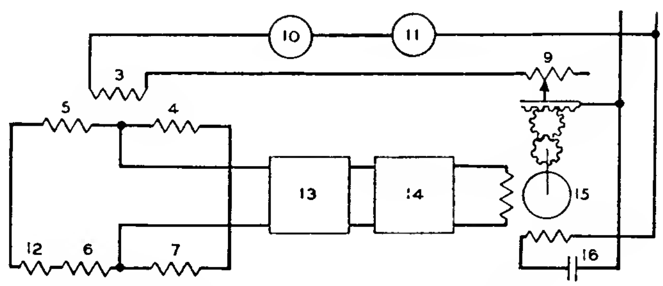


Exhibit V: **Automatic electronic control**

3. *Heater coil*
4, 5. *Resistance thermometers*
6, 7. *Fixed resistors*
9. *Current regulator*
10. *Wattmeter*
11. *Watt-hour meter*
12. *Compensating coil*
13. *Voltage amplifier*
14. *Power amplifier*
15. *Motor*
16. *Phase shifting capacitor*

Exhibit VI: Prototype Model Flowmeter.

An Electric Flow Meter

J. H. LAUB
MEMBER AIEE

A new instrument for accurately measuring, recording, and controlling the rate of flow, as well as the total flow, of fluids applies an electrocaloric principle. A wattmeter is used to indicate and record the rate of flow and a watt-hour meter to register the total flow. The scale of the meter is linear and covers a very wide range.

THE commonly used types of flow meters for liquids and gases are based on "mechanical" principles such as the measurement of the pressure drop across an orifice or the displacement of a nutating piston, propeller, or vane inserted into the flow of the fluid to be measured. Frequently, the primary mechanical magnitude so measured then is converted into an electric signal for remote controlling or metering purposes.

The widely used pressure drop or head-type flow meter[1] measures the differential pressure head created by the passage of the fluid through an orifice, flow nozzle, or Venturi tube (Figure 1). This pressure head Δh is proportional to the square of the rate of flow M. A meter with a nonuniform scale results, therefore, whose range is rather limited. A number of methods have been developed for converting the square root relationship into a linear one to obtain a meter with a uniform scale such as the Ledoux-bell or special desquaring cams. A constant pressure drop is obtained in the rotameter by employing a float within a tapered glass tube which serves as an orifice with variable opening. Its position is read on a uniform scale, the range being limited by the length of the glass tube.

In flow meters of the mechanical type, auxiliary devices are required to convert the original magnitude measured, for instance, the position of a float or a vane or the speed of revolution of a propeller, into an electric signal if remote metering or controlling is desired. In flow meters of the volumetric displacement type, electric tachometers may be used, for example, as converters. In head-type flow meters a magnetic plunger frequently is connected to the float whose movement within an inductance coil unbalances an a-c bridge circuit and thus produces an electric signal.

It is apparent from this brief discussion that considerable advantages could be expected from a flow metering method which would eliminate

1. A nonlinear relationship between flow rate and measured value with an attendant gain in accuracy and scale range.

2. The need for converting a mechanical signal into an electric one.

3. Direct contact between the measuring elements and the fluid and difficulties which result from contamination, corrosion, or leakage.

THE ELECTROCALORIC METHOD

If heat energy is introduced into or withdrawn from a medium flowing within a conduit and its temperature measured before and after the heat exchange (Figure 2) the differential temperature Δt between the upstream and downstream thermometer readings will vary with the rate of flow. It will be small for high flow rates and large for low flow rates and if Q denotes the heat flow in gram calories per second through the thin walls of the conduit of small diameter of Figure 2, M the rate of flow in grams per second, c the specific heat of the fluid in calories per degree centigrade per gram,

$$Q = cM\Delta t \tag{1}$$

if heat losses by conduction and radiation can be neglected against heat convection by the fluid.

If Q is produced electrically in a heater coil wound in close thermal contact with the outside wall of the conduit and well-insulated otherwise, the wattage input W to the heater coil is proportional to Q,

$$W = kQ \tag{2}$$

and equation 1 becomes

$$W = kcM\Delta t \tag{3}$$

and

$$M = \frac{1}{kc}\frac{1}{\Delta t}W \tag{4}$$

From equation 4 it follows that if the wattage input W were kept constant and the temperature differential Δt measured, the rate of flow M would be inversely proportional to Δt and would have to be read on a meter with a nonuniform, that is, hyperbolic, scale. If, however, the temperature difference Δt is kept constant by varying the wattage input W to the heater coil, the rate of flow M is proportional to W and can be read on the linear scale of the wattmeter measuring W. This can be accomplished if, instead of the two mercury thermometers in Figure 2, resistance thermometers are used and connected to a Wheatstone bridge circuit which is kept in balance for a given temperature difference Δt. If the balance is disturbed by a change in the rate of flow M, it is restored by adjusting the wattage input W to the heater coil,

J. H. Laub is assistant to the president, Charles Engelhard, Inc., East Newark, N. J.

The author acknowledges assistance in the development of the new flow meter from John Kremer of the engineering department of Charles Engelhard, Inc.

either manually or automatically. The resistance thermometers can be made, for instance, of nickel wire which has a high temperature coefficient of resistance and can be wound on the outside of the conduit in close thermal contact with its wall and well-insulated otherwise. A flow metering system thus is obtained, all of whose measuring elements are arranged outside of the fluid, which does not require conversion into an electric signal and which permits the rate of flow to be read on an instrument with a uniform infinite scale. It should be noted also that this flow metering system causes much less pressure drop in the line than mechanical flow meters of the pressure drop type.

Furthermore, totalizing of the flow can be achieved simply by adding to the heater coil circuit a watt-hour meter which then will register the total quantity of the fluid which has passed through the meter. This follows from integrating both sides of equation 4,

$$\int M d\tau = \frac{1}{kc}\frac{1}{\Delta t}\int W d\tau \qquad (5)$$

if τ denotes the time.

The left side of equation 5 represents the totalized flow which is seen to be proportional to the wattage W integrated over any period of time and can be measured by a watt-hour meter.

Thus, we have arrived at a caloric electric system for measuring rate of flow as well as total flow, the basic elements of which are illustrated in Figure 3. A tube section *1* of a metal with high heat conductivity is inserted into the fluid line and thermally insulated from it by insulating spacers *2*. On it are wound a heater coil *3* and the downstream resistance thermometer *4*, both in intimate thermal contact with the outside wall of section *1* and well-insulated otherwise. The upstream resistance thermometer *5* is wound on the outside wall of the fluid line and is separated from section *1* by one of the insulating spacers. Thermometers *4* and *5* form two arms of a Wheatstone bridge, the circuit of which is completed by two fixed and thermo-constant resistors *6* and *7*, respectively, and by a Null indicator *8*. In series with the heater coil *3* are connected a current regulator *9* which may be operated automatically from the Null indicator *8*, a wattmeter *10* calibrated to read rate of flow, for instance in pounds per hour, and a watt-hour meter *11* which registers the totalized flow, for instance, in pounds.

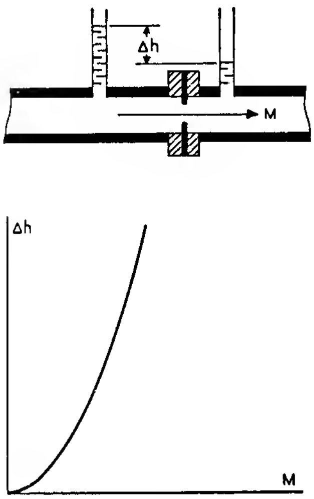


Figure 1. Relation between differential pressure and flow rate in a head-type flow meter

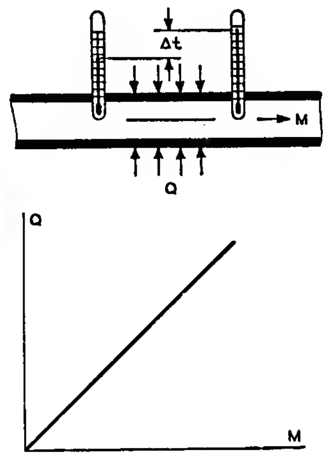


Figure 2. Relation between heat and flow rate in a caloric-type flow meter for constant differential temperature

SHUNT ARRANGEMENT

If large quantities of a fluid are to be measured, a substantial wattage would be required to maintain a satisfactory temperature differential Δt with the arrangement of Figure 3. This would necessitate a heater coil of large dimensions and thus introduce an objectionable time lag. Instead, the arrangement illustrated in Figure 4 is used for larger flows. A portion of the flow is shunted through a by-pass into which is inserted the section *1* carrying the heater coil *3* and the downstream thermometer *4*, again heat-insulated by means of spacers *2*. The upstream thermometer *5* now is wound on the main line and thermometers *4* and *5* again are connected into a Wheatstone bridge.

A small positive pressure head is maintained between inlet and outlet of the shunt by means of an orifice inserted in the main line a short distance ahead of the outlet. It will be noted that this arrangement is similar to the common shunt method of measuring large electric currents.

TEMPERATURE COMPENSATION

So far we have not considered the effect of varying fluid temperatures on the accuracy of flow measurements with the electrocaloric method. Referring again to equation 3 we note that wattage W and flow rate M are

proportional as long as the specific heat of the fluid remains constant. The latter is practically constant within a wide range of temperatures for most gases but varies somewhat for most liquids. For aviation gasoline of 0.702 specific gravity, for instance, the specific heat is 0.49 at 0 degree centigrade and increases proportionally with temperature to 0.55 at 50 degrees centigrade, that is, at the rate of approximately 1/4 of 1 per cent per degree centigrade.

Furthermore, we have to consider the effect of temperature on the viscosity of the fluid. It increases for gases and decreases for liquids with increased temperature, and thus affects, to a certain extent, the character of the flow and the mechanism of the heat transfer between the coils and the fluid. Without going into the details of the rather involved theory of fluid flow and heat transfer in pipes[3], a reminder that the local velocity of the fluid within a conduit is by no means uniform must be sufficient. The velocity distribution is governed by the Reynolds number which is inversely proportional to viscosity and therefore a function of fluid temperature. For Reynolds numbers below approximately 2,100, the motion of the fluid becomes streamline and the local velocity rises from zero at the wall to a maximum at the center along a parabolic distribution curve. For Reynolds numbers greater than approximately 2,100, the flow is turbulent and the velocity distribution curve rises more sharply from zero at the wall to a maximum at the center.

It is obvious, therefore, that the heat transfer from the wall to the fluid is affected by the character of the flow in the neighborhood of the wall, that is, by the temperature of the fluid. As a result of this, a flow meter as described so far shows a considerable temperature error. Fortunately, the latter practically can be eliminated by the simple and purely electrical compensation shown in Figure 4. A small coil *12* of wire with a high temperature coefficient of resistance, for instance, nickel, is wound on the conduit and in intimate thermal contact with it. It is connected in series with the constant resistor *6* in one branch of the bridge and, as its resistance varies with the temperature of the fluid, the over-all effect is a slight shift of the bridge balance with temperature. This method of temperature compensation is so effective that in the previously cited instance of aviation gasoline, the temperature error can be held under ± 1/2 of 1 per cent within a temperature range from 0 degree centigrade to 50 degrees centigrade.

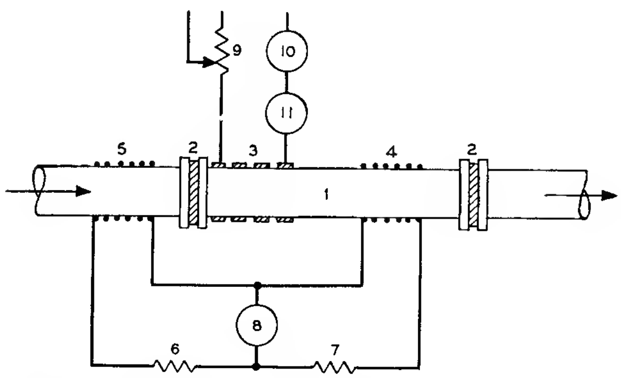


Figure 3. Basic elements of an electrocaloric flow meter

1. *Heater tube section*
2. *Insulating spacers*
3. *Heater coil*
4, 5. *Resistance thermometers*
6, 7. *Fixed resistors*
8. *Null detector*
9. *Current regulator*
10. *Wattmeter*
11. *Watt-hour meter*

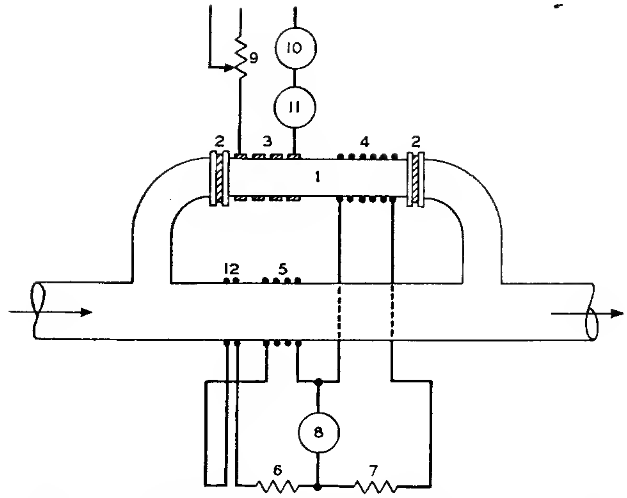


Figure 4. By-pass flow meter with temperature compensation

1. *Heater tube section*
2. *Insulating spacers*
3. *Heater coil*
4, 5. *Resistance thermometers*
6, 7. *Fixed resistors*
8. *Null detector*
9. *Current regulator*
10. *Wattmeter*
11. *Watt-hour meter*
12. *Compensating coil*

Variations of the ambient temperature will not affect the meter if the coils are heat-insulated well from the surrounding air and if the entire "transmitter" is enclosed in a metal cover which is in good heat-conducting contact with the pipe fittings and the fluid.

AUTOMATIC ELECTRONIC CONTROL

Rebalancing of the bridge is accomplished automatically by a simple electronic circuit (Figure 5). It consists essentially of a voltage and power amplifier in series which step up the signal from the a-c bridge sufficiently to operate a 2-phase reversible induction motor which drives the rheostat that regulates the current to the

heater coil. The second phase of the motor is energized from the a-c supply line, its current being displaced 90 degrees from the current in the first phase by means of the capacitor connected in series with it. As is well known, this arrangement has phase discriminating characteristics and the motor will reverse its direction of rotation when the signal from the bridge goes through zero and reverses its phase.

A similar arrangement is used for automatic control of the flow. In this instance the motor regulates a valve in the fluid line instead of driving the rheostat which then is set at a predetermined value corresponding to any desired rate of flow.

The electronic circuit described provides a continuous and very sensitive control that reacts immediately to minute changes in flow rate.

It should be noted also that fluctuations of the line voltage will not cause any error in indication. If, namely, the voltage varies the automatic control immediately will restore the wattage input to the heater coil which is demanded to maintain the fixed temperature differential Δt for a given rate of flow.

An example of the new electrocaloric flow meter is illustrated in Figure 6. The instrument shown is designed to measure the rate of flow and the total flow of aviation gasoline with a range from 0 to 2,000 pounds per hour. The transmitter consists of a by-pass arrangement with a 1-inch diameter main line and a 5/8-inch diameter shunt on which the heater coil of nichrome wire is wound. The maximum input to the latter is 50 watts corresponding to a flow rate of 2,000 pounds per hour. It is measured by a long scale indicating wattmeter[4] calibrated in pounds per hour. The watt-hour meter registers the total flow and is calibrated in pounds and the two instru-

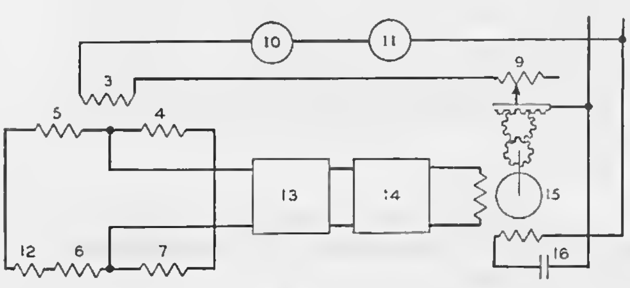
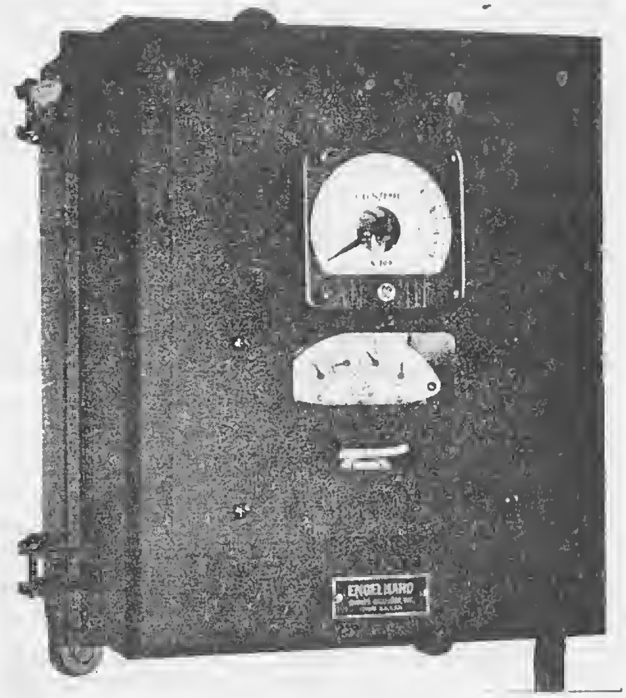
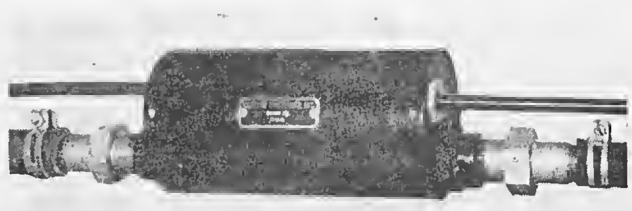


Figure 5. Automatic electronic control

3. *Heater coil*
4, 5. *Resistance thermometers*
6, 7. *Fixed resistors*
9. *Current regulator*
10. *Wattmeter*
11. *Watt-hour meter*
12. *Compensating coil*
13. *Voltage amplifier*
14. *Power amplifier*
15. *Motor*
16. *Phase shifting capacitor*



A—Receiver



B—Transmitter

Figure 6. Electric flow meter for gasoline 0–2,000 pounds per hour indicates rate of flow on wattmeter and registers totalized flow on watt-hour meter

ments are mounted in the hinged front panel of the receiver case. The electronic control unit consisting of amplifier, motor, and rheostat is mounted inside of the case on the rear panel and is easily accessible.

Transmitter and receiver can be separated by any convenient distance if remote control or metering is required without affecting the accuracy of the instrument. If a permanent record of the rate of flow is desired, a recording wattmeter of conventional design is used instead of the indicating wattmeter.

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MEASURING MASS FLOW with the boundary-layer flowmeter

The electrocaloric flowmeter of the boundary-layer type features an essentially linear scale over a major portion of its range, is impervious to chemical attack when constructed with the proper materials, and uses a smooth-bore flow transmitter which introduces a negligible pressure drop. It also has no leakage or sealing problems, requires little maintenance or cleaning, and is simple to install in the process piping. All these characteristics make the flowmeter particularly advantageous in measuring and controlling mass-flow rate.

The author describes the underlying theory of the boundary-layer flowmeter, the considerations involved in designing and constructing a practical flowmeter, and the application of the flowmeter in closed-loop control systems using either electric or pneumatic actuators.

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When fluid flows in a conduit a thin film of fluid particles forms on the conduit's inside surface. This film, partly adhering to the surface and partly in laminar flow parallel to the surface, is called a boundary layer. The amount of heat required to develop a known temperature difference across the boundary layer indicates the heat transfer rate, and this rate through the boundary layer is a measure of the fluid's mass-flow rate. Thus, the heat injected becomes a measure of the mass-flow rate.

A practical design of a flowmeter based on the boundary-layer principle is shown in Figure 1. Essentially, the flowmeter consists of an electric heating coil wound around the outside of the pipe and two resistance temperature detectors (which feed into a Wheatstone bridge) also wrapped around the outside of the pipe—one upstream from the heater coil and the other downstream. The amount of power (watts dissipated in the heater coil) supplied to the fluid to maintain a constant temperature difference between the two temperature detectors indicates the mass-flow rate.

BOUNDARY-LAYER PRINCIPLE

Heat flowing radially inward from the heater coil in Figure 1 meets the following obstacles in its path: a thin layer of insulation between the heater coil and the conduit's outside surface, the wall of the conduit, the boundary layer, and the main core of the fluid. Radial heat transfer through the boundary layer takes place by conduction, since there is no interchange of fluid particles with the main core. If the main core is in turbulent flow the transition from laminar to turbulent motion occurs in an intermediary buffer layer. Here eddy currents develop, resulting in radial motion of fluid particles and heat transfer by convection. Thickness of the boundary layer varies with velocity of the fluid stream, [1,2,3].

Under turbulent-flow conditions the boundary layer is the main barrier to heat transfer and thus requires the major share of the temperature difference between the heat source and the center of the conduit. Figure 2 shows the radial temperature distribution in the conduit. The solid line characterizes the conditions of turbulent flow (Reynolds numbers greater than 2,100). At flow velocities in the laminar range (Reynolds numbers less than 2,100) the temperature decreases more gradually from the wall to the conduit axis (dashed line).

Heat transfer rate

If a quantity Q of heat is transferred through an area A of thermal transmittance U, a temperature gradient Δt results:

$$Q = UA\,\Delta t \tag{1}$$

Here the temperature gradient Δt represents the total of the temperature gradients across all barriers to heat flow. Normally in a boundary-layer flowmeter of the type shown in Figure 1, all temperature gradients, except that across the boundary-layer, will be negligible. For the sake of completeness, however, the temperature gradient across the conduit wall as well as that across the boundary layer are included in the following analysis:

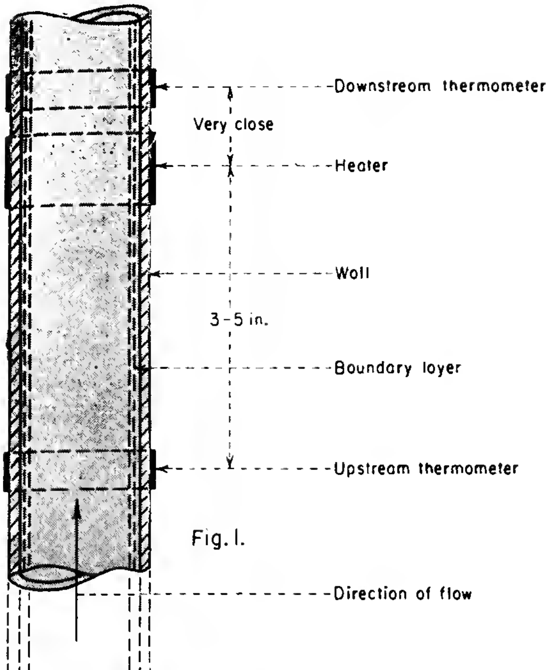


Fig. I.

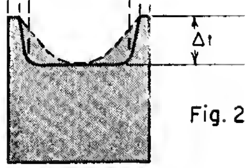


Fig. 2.

FIG. 1. In a well-designed boundary-layer flow transmitter of the type shown here, the amount coil to maintain a known temperature difference coil to maintain a known temperature difference between the upstream and downstream thermometers indicates the mass flow rate of the fluid.

FIG. 2. The radial temperature distribution through the core of the fluid depends on whether the flow is turbulent or laminar. For turbulent flow the major temperature drop is across the boundary layer (solid line), but for laminar flow conduction between fluid particles causes the temperature gradient to change gradually toward the center of the fluid core.

The transfer of Q through the wall requires a temperature gradient Δt_w:

$$Q = k_w A \, \Delta t_w \tag{2}$$

where k_w is the wall's thermal conductance. The transfer of Q through the boundary layer requires a temperature differential Δt_b which can be calculated from:

$$Q = hA \, \Delta t_b \tag{3}$$

where h is the film conductance of the boundary layer.

The total temperature difference Δt is the sum of Δt_w and Δt_b:

$$\Delta t = \Delta t_w + \Delta t_b = \frac{Q}{A}\left(\frac{1}{k_w} + \frac{1}{h}\right) \tag{4}$$

Thus:

$$Q = A \, \Delta t \frac{1}{\frac{1}{k_w} + \frac{1}{h}} = C \frac{k_w h}{h + k_w} \tag{5}$$

Equation 5 describes how Q varies with h for a given wall conductance k_w if Δt is held constant. When the conduit walls are thin and have high thermal conductivity k_w becomes much larger than h and Equation 5 simplifies to:

$$Q = A \, \Delta t \, h \tag{6}$$

The film conductance h is a function of the mass rate of flow, the properties of the fluid, and the dimensions of the conduit. Reynolds first established the relationship between the various parameters by applying the analogy between heat transfer and momentum transfer in a fluid. The results, later confirmed by dimensional analysis, can be written in the form known as Nusselt's expression:

$$Nu = C(Re)^p \times (Pr)^q \tag{7}$$

in which Nu is the Nusselt number, Re is the Reynolds number, and Pr is the Prandtl number of the fluid. These numbers are defined as follows:

$$Nu = hD/k \tag{8}$$

$$Re = DV\delta/\mu = DG/\mu \tag{9}$$

$$Pr = c\,\mu/k \tag{10}$$

where D is the conduit's inner diameter
k is the fluid's thermal conductivity
c is the fluid's specific heat
μ is the fluid's absolute viscosity
δ is the fluid's density
V is the fluid's average velocity
G is the fluid's average velocity $\times$ mass density $= V\delta$

For turbulent conditions (Re greater than 2,100) close agreement between experimental results and the Nusselt equations is obtained with $C = 0.023$; $p = 0.80$; and $q = 0.40$. Equation 7 then becomes[4]:

$$\frac{hD}{k} = 0.023\left(\frac{DV\delta}{\mu}\right)^{0.8}\left(\frac{c\,\mu}{k}\right)^{0.4} \tag{11}$$

which can be written:

$$h = 0.023 \frac{k^{0.6}\,c^{0.4}}{D^{0.2}\,\mu^{0.4}} G^{0.8} \tag{12}$$

Equation 12 applies to the entire range of turbulent flow, except for viscous liquids where it is valid only for Re greater than 10,000. This equation satisfies practically the entire range of a flowmeter for low-viscosity fluids, since a Reynolds number of 2,100 corresponds to approximately 2 percent of the maximum flow-rate in an actual design.

For flow velocities less than $Re = 2{,}100$ the flow is laminar. Under these conditions the film conductance can be expressed by the empirical formula[5]:

$$h = 2.34 \frac{k^{2/3}\,c^{1/3}}{(DL)^{1/3}} G^{1/3} \tag{13}$$

where L is the length of the heated surface.

For zero flow (Re equals zero) the film conductance is so small for most fluids, compared with the conduit wall's longitudinal conductance, that it can be neglected. The longitudinal conductance is deter-

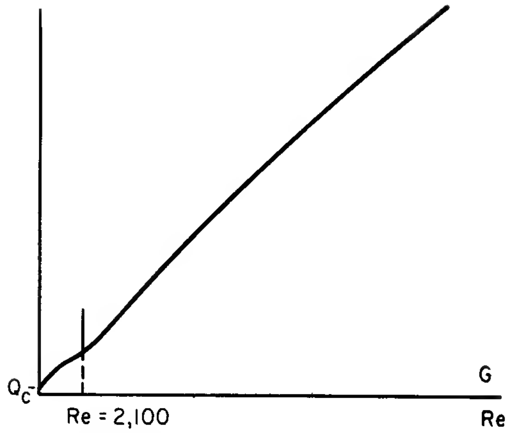


FIG. 3. Over the major portion of the flowmeter range the amount of heat input varies almost linearly with the product of the average mass velocity and density (G), where G is proportional to the mass flow rate F, lb/hr.

mined by the wall's annular area and thermal conductivity and the spacing of the temperature detectors from the heater.

Equations 12 and 13 show the dependence of film conductance h on G, the product of the fluid's average velocity and mass density. But the mass flow rate F, in which terms the flowmeter is actually calibrated, equals G times the cross-sectional area of the conduit.

Heat input vs. mass-flow rate

The relationship between heat input (Q Btu) and G (hence F) can now be found over the entire range of mass-flow rates by inserting the values of h obtained for the three flow-rate conditions in Equation 6. If Δt is held constant Q is proportional to h. For a given stream composition (k, c, and μ constant) and a given design (D constant) Equation 12 (for the turbulent range) shows that Q varies with the 0.8 power of G. For the laminar range Equation 13 shows that Q varies with the $\frac{1}{3}$ power of G. For zero flow Q assumes a (small) value determined by the parameters of the conduit.

Figure 3 shows graphically how the heat input varies over the entire flow-rate range. For zero flow the heat input is a minimum-value Q_c determined by the conduit's parameters. In the laminar region the slope corresponds to a cube root relationship. In the turbulent range (that is, almost the entire flowmeter range) the plot is practically linear.

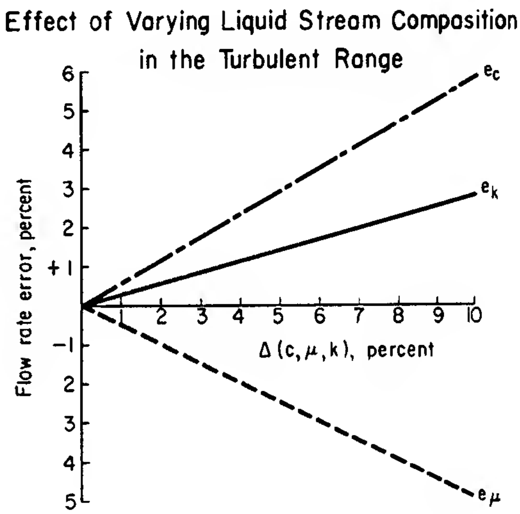
Stream composition and temperature

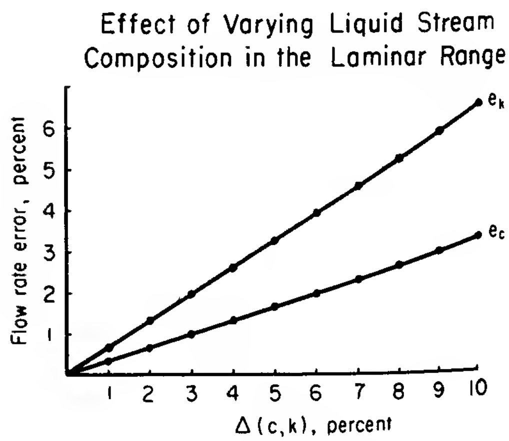
The preceding discussion covered the effect of varying flow rate on the heat transfer through the boundary layer, showing how a measurement of the temperature differential across the boundary layer can indicate the flow rate. Other factors, such as variations of the stream composition and fluid temperature, affect the heat transfer, too, and thus would produce flow rate errors unless accounted for.

In some applications of the boundary-layer mass flowmeter the stream composition will vary, even with a constant temperature, within certain limits and the fluid parameters k, c, and μ, appearing in the Prandtl number, will not remain constant. Equations 12 and 13 show how these variations affect the film conductance of the boundary layer in the turbulant and laminar range, and Equation 6 reveals the resulting effect on Q when Δt is held constant.

For gas streams the Prandtl number is very nearly independent of the composition, and flow-rate errors due to variations in this factor thus become negligible.

Composition variations of liquid streams introduce flow-rate errors, the magnitude of which can be determined for the turbulent and laminar regions. Errors in the turbulent range, according to Equation 12 and 6, are proportional to the 0.4th power of c,





FIGS. 4 and 5. Stream composition variations (changes in specific heat, c, thermal conductivity k, and viscosity μ) appear as errors in flow-rate indication in the turbulent range (Figure 4). The percentage error is less than proportional to the change in the variable. For laminar flow, Figure 5, only variations in c and k introduce errors.

so that a 5-percent change in the specific heat results in less than a 2-percent error in flow-rate indication. Since the error is inversely proportional to the 0.4th power of μ, the error will be reduced or will become zero if both specific heat and viscosity increase or decrease together. A change in the stream composition ordinarily has little effect on the thermal conductivity k of a liquid, but if any change in k does occur the resulting error in flow-rate indication is less than proportional to the variation in k. This is true for both laminar and turbulent flow, as shown in Figures 4 and 5.

In the laminar range, Equation 13 shows that variations of c have little effect on the flow-rate indication since h is proportional to the cube root of c. Variations of μ need not be considered in the laminar range because this parameter does not influence the film conductance h, as can be seen from Equation 13.

In a stream of fixed composition c, k, and μ will also normally change with a variation in stream temperature. The effect may be substantial for liquids, but negligible for gases. The effect of stream temperature variations can be assayed by determining the change in c, k, and μ over the expected temperature variation, and the resulting change in h from Equations 6, 12, and 13. Since temperature variations may be considerable, temperature compensation must be included in the flowmeter design for liquids to minimize indicated errors of flow rate. The compensation is easily accomplished in the bridge circuit by winding a temperature-sensitive resistance around the pipe and connecting this resistance in series with one of the fixed resistors in the bridge[6]. In this way the bridge responds only to variations of flow rate and not of temperature.

DESIGNING A FLOW-RATE TRANSDUCER

In theory, implementation of the boundary-layer principle as a mass-flow measuring method requires temperature measurements on both sides of the boundary layer to obtain Δt. But this is impractical on several counts: the boundary layer is only several thousandths of an inch thick and varies in thickness with the fluid and Reynolds number; thus one fixed position of the internal temperature detector would not satisfy all possible conditions. Also, a temperature detector located inside the pipe becomes subject to corrosive influences, obstructs the flow, increases pressure drop, can be attacked by fluid and solid particles, and introduces a sealing problem.

In practice, both temperature detectors for measuring Δt are located outside the pipe, as shown in Figure 1. With proper design, this arrangement measures the Δt across the boundary layer, as can be seen from the following analysis: the upstream thermometer, located about 3-5 in. away from the heater coil, is unaffected by the heat injected into the stream by the heater coil and thus the thermometer can be assumed to be measuring the inside temperature of the boundary layer. The heat injected into the stream by the heater coil raises the temperature of the pipe wall which, because of its small thermal resistance, is essentially the same temperature as the outside of the boundary layer. This temperature is measured by the thermometer immediately downstream from the heater coil. Thus the inside of the heater coil, the pipe wall near the heater coil, and the outside of the boundary layer are all considered as being at the same temperature, Δt higher than the temperature inside the boundary layer.

Calculating the power input

The quantity actually measured in the flowmeter is not Q, but the wattage W dissipated in the heater coil and measured by a wattmeter. Thus a wattmeter, calibrated in terms of mass flow, serves as the indicating instrument for the boundary-layer mass flowmeter.

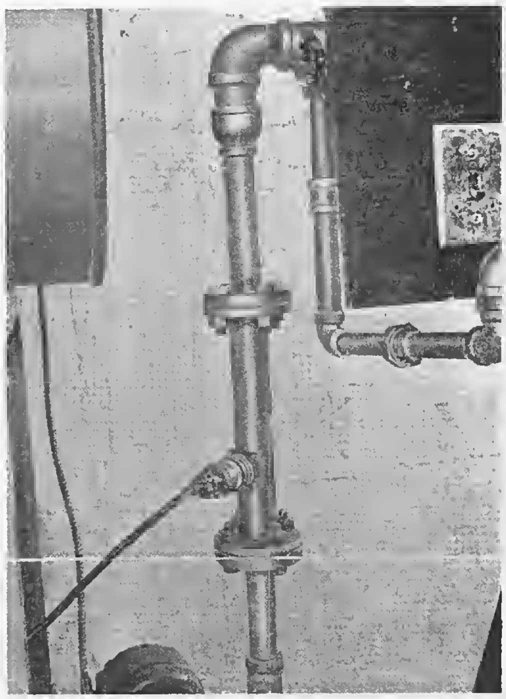


FIG. 6. The boundary-layer mass flow transmitter shown here is steel-jacketed to protect it against external damage and to hermetically seal the measuring elements. The AN-type electrical connector assures correct connection of leads to the indicating and control instruments.

The heat transfer to the fluid as a function of the rate of fluid flow in the turbulent and laminar range can be calculated from Equations 6, 12, and 13 if the fluid properties are known. The maximum heat flow Q_m, which corresponds to the maximum flow-rate of a flowmeter of given design, can thus be readily determined.

A flowmeter with a maximum mass-flow rate F of 12,000 lb/hr of water in a conduit of $1\frac{1}{2}$ in. in diam

serves as a design example. Here $F = G$ times area of conduit. The parameters to be inserted into Equation 12 are:

$D = 0.125$ ft
$k = 0.364$ Btu/hr (sq ft) (deg F/ft)
$c = 0.997$ Btu/lb/deg F
$\mu = 1.65$ lb/(ft) (hr)
$\delta = 61.99$ lb/cu ft
$V = 15{,}770$ ft/hr
$G = 976{,}000$ lb/sq ft hr
$Re = 74{,}000$
$Pr = 4.51$

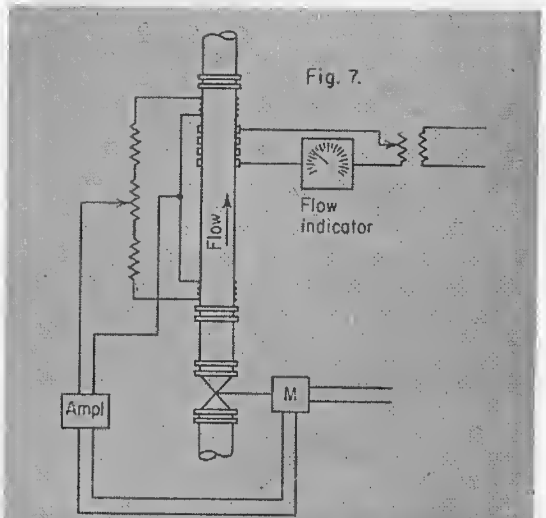
This yields a maximum value of the film conductance h.

$$h_m = 0.023 \frac{0.364^{0.6} \times 0.997^{0.4}}{0.125^{0.2} \times 1.65^{0.4}} 976{,}000^{0.8}$$
$$= 961 \text{ Btu/hr ft}^2 \text{ deg F}$$

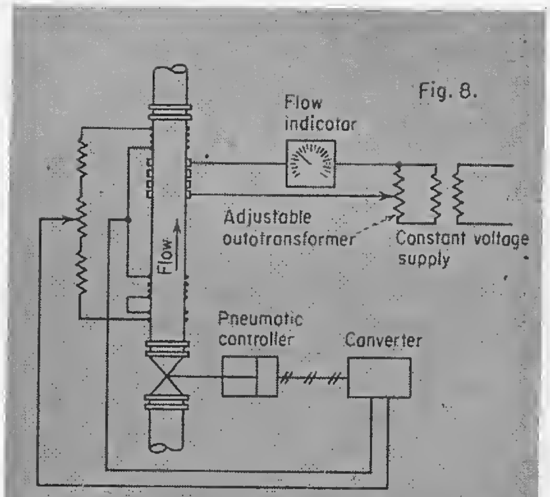
The heater coil of this flowmeter is 2 in. long and has an ID of 1.655 in., resulting in a heat transfer area A equal to 0.0722 ft². If Δt is 2 deg F, Equation 6 yields:

$$Q_m = 961 \times 0.0722 \times 2 = 138.8 \text{ Btu/hr} = 40.8 \text{ watts}$$

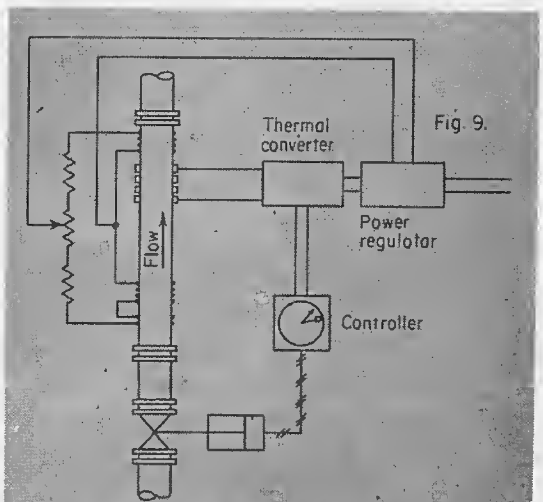
Δt is maintained constant by connecting the two resistance thermometers in a self-balancing Wheatstone-bridge circuit. Automatic adjustment of the heater input power, where the input power indicates the mass-flow rate, is obtained by a servo loop with a motor-driven power regulator or by a purely electronic control circuit which eliminates contacts and mechanically moving parts. In the electronic circuit an unbalance in the bridge caused by a change in flow rate is detected and amplified. The phase of the unbalance signal depends on whether the flow



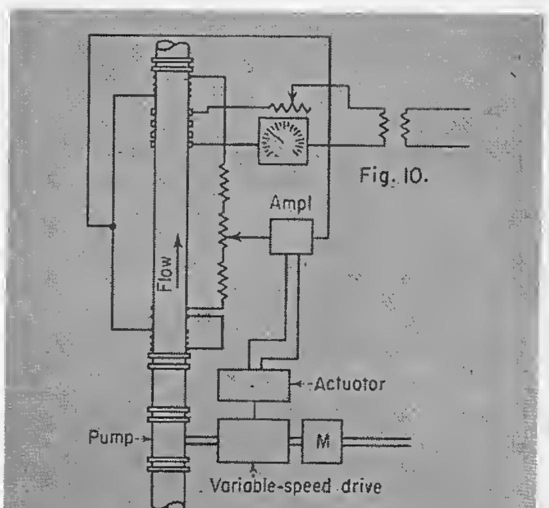
Mass Flow Control with Electrical Valve Actuator



Mass Flow Control with Pneumatic Valve Actuator



Mass Flow Control using Conventional Millivolt Controller and Thermal Converter



Mass Flow Control with Variable-speed Pump

increases or decreases and is discriminated by a triode which controls the charge of a capacitor. The capacitor forms part of an R-C network whose time constant matches that of the thermal analog of the flow-measuring transducer. The voltage across the capacitor controls the firing angle of a pair of push-pull thyratrons which provide smooth regulation of the wattage input to the heater coil. This power supply control circuit is independent of line voltage variations over a wide range.

In designing and constructing a boundary-layer flow transmitter, due consideration must be given the needs of the process fluid while still adhering to the theoretical requirements of the boundary-layer principle. Fluid pressure and corrosive action determine the material and wall thickness of the transmitter conduit. The material should be of high thermal conductance to introduce a small or negligible temperature drop (compared with the temperature drop across the boundary layer) across the conduit's wall. The insulation between the heater coil and temperature detectors and the outside surface of the conduit should be thin and of the highest practical thermal conductivity, again to introduce a small or negligible temperature drop. On the other hand, the outside surfaces of the heater coil and temperature detectors should be well-insulated to assure that all power dissipated in the heater coil goes into the boundary layer and not into the surrounding air. Figure 6 shows a typical boundary-layer mass-flow-rate transmitter installed for an industrial application. Flange connectors permit transmitter removal for cleaning the bore without disturbing the associated piping.

CLOSED-LOOP FLOW CONTROL

Closed-loop control of mass flow rate with the boundary-layer flowmeter is a simple matter for systems using either electrical or pneumatic actuation. Figure 7 shows how proportional control of flow is obtained in processes controlled by an electrically-operated valve. The desired rate of flow is selected by adjusting the wattage input to the heater coil corresponding to the desired rate. Flow-rate indication appears on a calibrated wattmeter in the circuit of the heater coil which is supplied from a constant voltage source. A flow-rate deviation from the desired value produces an unbalance signal in the bridge equivalent to a change from the established Δt. The signal is amplified and fed into the control winding of the motor driving the valve. The valve automatically opens or closes to change the flow until the established Δt, corresponding to the desired flow rate for the fixed wattage input, is restored. For on-off control, in a bypass to a main line, for instance, the unbalance signal drives a solenoid-operated valve.

For pneumatic control, the electrical unbalance signal is converted into a corresponding pneumatic signal for the actuation of the pneumatic-actuated flow control valve. Figure 8 illustrates this method.

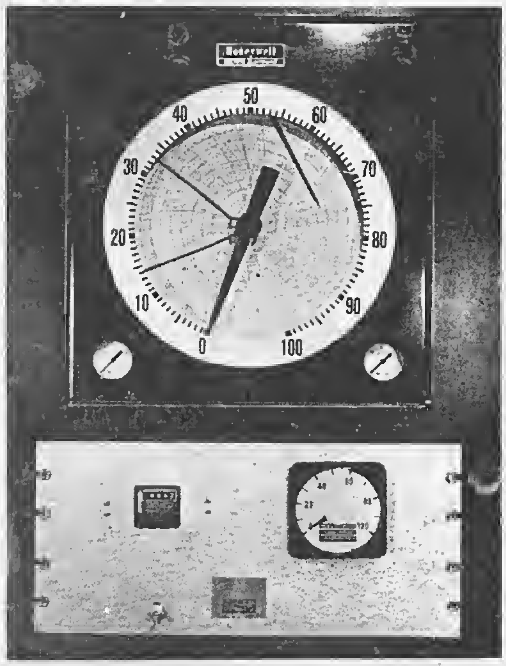


FIG. 11. The electrical signal from the flow transmitter is converted into a pneumatic control signal in a conventional recorder-controller while instantaneous flow rate and total flow appear on the lower panel.

For control systems, Figure 9, employing conventional millivolt recording-controlling instruments with electrical or pneumatic outputs, a thermal converter changes the heater coil input power into a dc voltage which is fed into the self-balancing potentiometer controller. Then the rate of flow is set by the index pointer of the recorder-controller.

In cases where a variable-speed pump controls the flow rate, the unbalance signal is amplified and fed into a reversible motor-actuator which changes the ratio of a variable speed drive to adjust the pump speed. Figure 10 shows this method of controlling the flow from the boundary-layer mass flowmeter.

Figure 11 shows the indicating-recording-controlling section of a flow-measuring installation. (Transmitter installation was illustrated in Figure 7.) The recorder-controller, top, converts the electrical output from the transmitter to a corresponding pneumatic signal. At the bottom left the counter-like device totalizes the flow, while the indicator at the right shows instantaneous flow.

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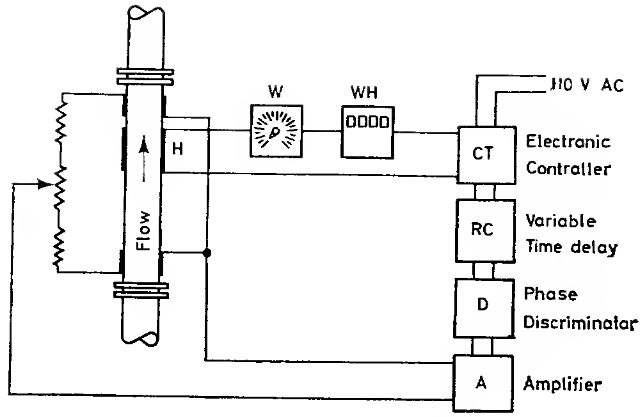

Exhibit IX: Schematic of Variable Power Mode of Operation

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THERMAL FLOWMETER

Filed Oct. 9, 1958

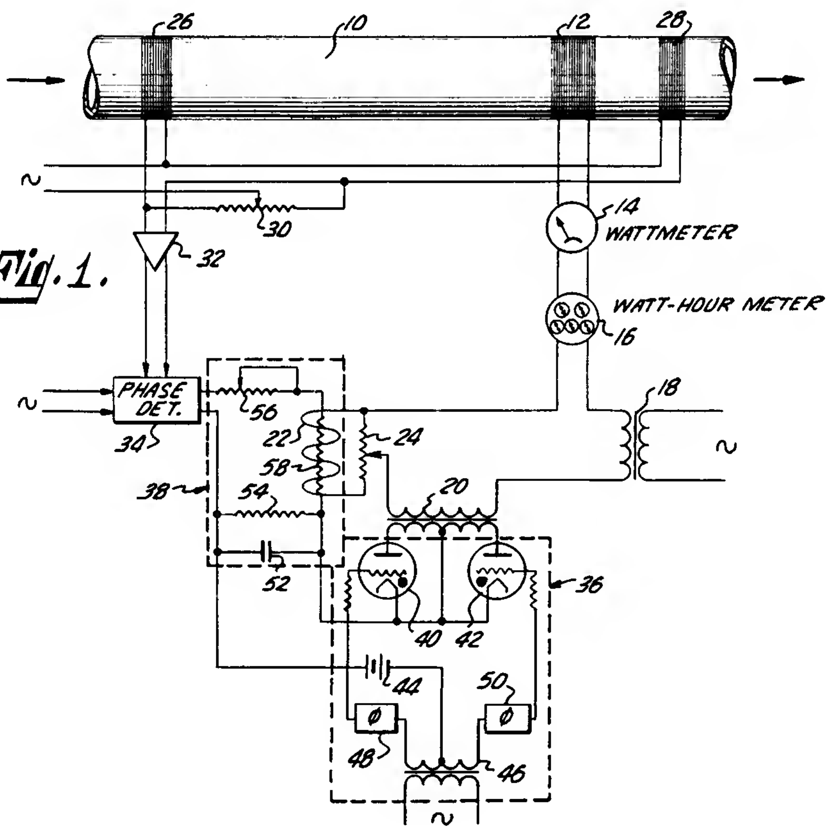

Fig. 1.

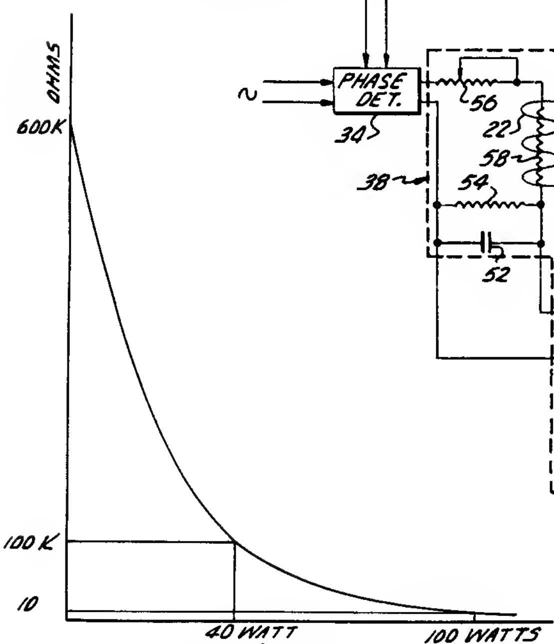

Fig. 2.

INVENTOR.
JOHN H. LAUB

BY Christie, Parker & Hale

ATTORNEYS.

Exhibit X:

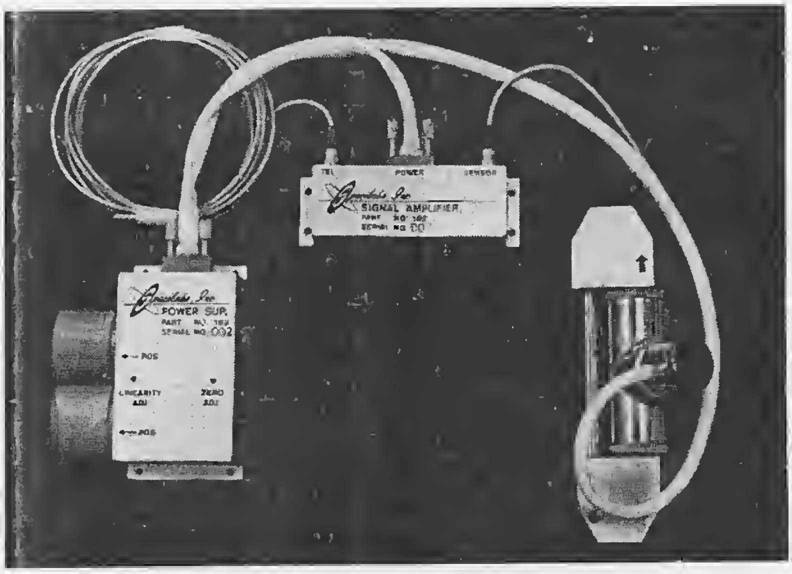

Exhibit XI: Boundary Layer Flow Meter for Telemetering of Breathing Rate of Astronauts

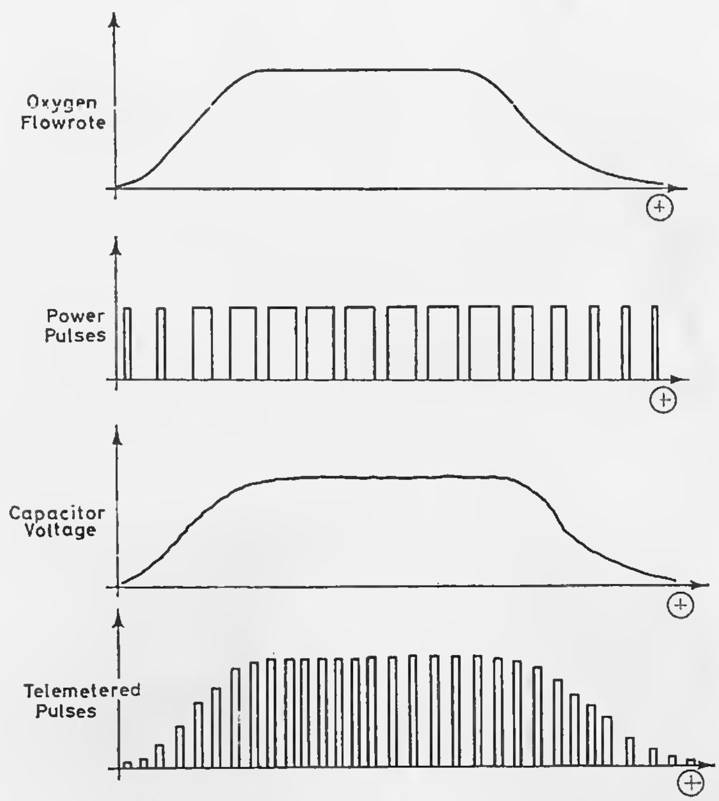

Exhibit XII: Telemetering of Oxygen Flow Rate by Pulse Width Modulation

Exhibit XIII: